

Electrostatically-Actuated Microprobe for Time-of-Flight Mass Analyzer Scanning Force Microscopy

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論 文 内 容 要 旨

Since the invention of scanning tunneling microscopy (STM) and scanning force microscopy (SFM), these novel microscopy techniques have been developed for atomic imaging and manipulation. The SFM families are playing important roles and widely used in nanotechnology. SFM techniques enable us to obtain various physical properties on a surface in nanometer scale and opened up entirely new possibility for studying the structure and dynamics of individual molecules and atoms in surface science. One of the drawbacks of the SFM technique is that it did not have capability for chemical analysis of solid surface. Atom probe field ion microscopy (APFIM) is the first instrument that that has capability for atom observation and identification simultaneously. APFIM is combined with a field-ion microscopy (FIM) and mass analyzer (MA) for observation of atoms and chemical analysis and invented in 1968 by Muller et al. However a serious disadvantage of this instrument is related to the requirement that the sample needs to be formed as a sharp tip. The sharp tip is often formed by electron or ion milling technology. From above reason, the observation of atoms cannot be obtained but the chemical analysis of solid surface cannot be achieved. An additional difficult in the process is that sample material are limited to semiconductor or conductors. In order to satisfy the requirement of the physical properties such topography and chemical analysis of solid surface simultaneously, a new instrument combined with STM/SFM and mass analyzer (MA) can overcome above issues. In 2003, D.W. Lee et al. presented a thermal type probe assembled with an extraction electrode for time of flight-mass analyzer scanning force microscopy (TOF-MA SFM). TOF-MA SFM is a kind of scanning force microscopy (SFM) combining with a time-of-flight mass analyzer (TOF-MA). This combination system of SFM and mass analyzer is demonstrated to obtain topographical image of a surface with atomic resolution and identify individual molecule or atom on surface for chemical information simultaneously.

TOF-MA SFM system is based on a convention SFM system for surface imaging with atomic resolution and a TOF-MA system for chemical analysis of single ions. The system has two working mode, one is called as SFM mode, the other one is called as TOF-MA mode. For this combination of analyzing systems, an actuator-integrated probe is needed to switch those modes. In this SFM mode, the cantilever scans the sample surface and the

tip grabs a single atom or molecule. In TOF-MA mode, the picked up atom or molecule is lifted up to near in front of the extraction electrode and emitted by field-ionized evaporation to Mass Analyzer.

As earlier studies of TOF-SFM, the thermal bending actuator is the first used to assemble a extraction electrode for TOF-MA SFM. By heating the cantilever to 300°C, 60 μm of displacement can be obtained for measurement switching. However, in SFM mode, the thermal bending actuator easily causes thermal noise to reduce the resolution of topographic imaging. In TOF mode, precise assembling of the extraction electrode is important issue. In order to precisely emit target materials toward the TOF-MA, the tip of the probe must be precisely positioned in the center of the extraction electrode in TOF mode. To achieve this requirement, a non-thermal type actuator and no assembly process of extraction electrode have more benefit for high spatial resolution because of less thermal noise in SFM mode and precise alignment in TOF mode. In 2005, E. Meyer et al employed motorized rotatable holder with a probe is employed to change the working modes, in addition, the extraction electrode is assembled into the system for field-evaporation of target materials to the TOF-MA. In 2007 Kawai et al demonstrated that bimorph piezoelectric actuator has fast switching speed with less thermal noise, and the spring constant of the probe can be tuned for stable imaging of SFM. Both of these two kind non-thermal type actuators still need to assemble an extraction electrode for field evaporation.

The integration of the extraction electrode actuator and cantilever with a tip on the basis of batch fabrication is desired regarding to its high precision. In this study, we have proposed a novel TOF-SFM probe with an electrostatic actuator and extraction electrode, which can be fabricated without assembling process. The electrostatic actuator integrated with curved electrodes is simple and easy to achieve large displacement to change position in MEMS application. We designed and fabricated a switchable cantilever probe with the electrostatic actuator employing curved electrodes for TOF-SFM. This electric actuator consists of a cantilever for surface scanning and manipulation action, a couple of curved electrodes for actuation of cantilever, stoppers distributed along the curved electrodes for tuning spring constant and prevent electrical shortage, capacitive vibration sensor for vibration of cantilever and extraction electrode for field evaporation. By electrostatic pull-in effect, the cantilever is attracted to the curved electrode and contacted to stoppers. In SFM mode, the cantilever is bent approach to sample surface for scanning and manipulation action. In TOF mode, the cantilever is bent upward and placed in front of the extraction electrode as well for emitting atom or molecule toward the TOF-MA with field-assisted evaporation. When the applied voltage of curved electrode is increased, the cantilever is attracted onto curved electrode and stepwise stuck on stoppers. When the cantilever is stopped at stoppers completely, the length of cantilever for vibration is become short by sticking cantilever on stoppers. The spring constant of the cantilever will be increased by the stepwise variation of the displacements.

In order to evaluate the characterization of electrostatic actuator for application of TOF-MA SFM, We design electrostatic actuators with different slope of curved electrodes and different geometries of cantilevers for evaluation. Firstly, for evaluation of actuation, we design and fabricated electrostatic actuator with an arc shape of curved electrodes. The shape of the arc is formed from a circle with 3500 μm diameter. The length, width, and thickness of cantilever are 1900 μm , 50 μm , and 10 μm . The actuator employing curved electrodes is like zipper actuator, the narrow gap between the curved electrodes and cantilever is d . The gap between the curved electrodes and cantilever are designed to become

wider at the end. The maximum gap between curved electrodes is 250 μm and this distance is called δ_{max} . In this case of the electrostatic actuators, the narrow gaps d are 10 μm , 13 μm and refer to type A1, type A2 actuator. The displacement was observed from the side using an optical microscope attached to a CCD camera. The driving voltage was applied between the curved electrode and the cantilever using a probe station. The driving voltage was slowly increased until the cantilever had reached on the stoppers. The displacement against applied voltage of type A1 actuator with 10 μm of narrow gaps d shows a larger displacement of approximately 52 μm was obtained at an applied voltage of 300 V. In the case of type A2 actuator with 10 μm , a displacement of 25 μm was obtained when an application voltage is near of 370 V. Comparison of these results shows the applied voltage is reduced by decreased the distance of narrow gap.

However, applied voltage over 300V is easily caused electrical breakdown to damage the cantilever; in order to reduce the high applied voltage, we modify the shape of curved electrodes using the method which reported by Legtenberg et al. The shape is designed by $S(x) = \delta_{\text{max}}(x/l)^2$, where x is the position along the x -axis, δ_{max} is the gap at the end of the curved electrode, and l is the length of the curved electrode. The gap between the curved electrodes and cantilever are designed to wider at the end. The same experiment setup is repeated for the static displacement of electrostatic actuator with modified curved electrodes. The modified curved electrodes have three values of δ_{max} , 50 μm , 110 μm , 150 μm , as type B1, type B2, type B3, and the length, width and the thickness of the type B1, type B2, type B3 actuators are 1900 μm , 50 μm and 5 μm . The static displacement characteristics of type A series and type B series electrostatic actuators are compared. In the case of type B series actuators, several pull-in phenomena are observed until the cantilever is completely stuck to the stoppers. In the case of type B1, the pull-in phenomenon was observed at the applied voltage of approximately 55 V, and the deflection of the cantilever abruptly changed from 14 μm to 66 μm . In the cases of type B2 and type B3, As the slope of curved electrode become larger, a large displacement can be obtained, but higher applied voltage is required for switching operation. After three times and two times of pull-in phenomena are observed for type B2 and type B3 electrodes, 157 μm of displacement was obtained for SFM mode after two times pull-in phenomenon at an applied voltage of 135 V. In addition, 255 μm of displacement was obtained for the TOF mode at an application voltage of 175 V. As the result shows the applied voltages is reduced by using above equation for modification of curved electrode and decrease the thickness of cantilevers.

In order to evaluate the capability of spring constant tuning by stiction to the stoppers and resonant frequency, the cantilever was vibrated by applying an AC actuation voltage to the lower curved electrode together with static actuation voltage the actuation voltage dependence on the resonant frequency is measured by a laser Doppler vibrometer. The vibration signals were detected using a network analyzer. The length, wide and thickness of this cantilever are 1900 μm , 50 μm , and 6 μm . The initial frequency of the cantilever with a type B2 curved electrode is 1.8 kHz at applied voltage 5V, where the cantilever was not stuck to any stoppers. After final pull-in effect, the cantilever is stuck on stoppers completely and the length for vibration shortens from 1900 μm to 600 μm . This cantilever was designed to exhibit a resonant frequency of 20 kHz and spring constant of 1.22 N/m by

employing the cantilever with an effective length of 600 μm and thickness of 6 μm after complete pull-in. However, one of the stoppers of curved electrode on free side is peeled off during isotropic wet etching process. Therefore, the effective length of cantilever is extended from 600 μm to 1000 μm . The measured resonant frequency of the cantilever with effective length is changed to 6.8 kHz at final pull-in effect. According to stepwise pull-in effect, the observed spring constant is changed from 0.04 N/m to 0.26 N/m. The result means the spring constant is tunable by sticking cantilever on stoppers.

During the cantilever is scanning sample surface, the interactive force between tip and surface will attract cantilever on surface, in order to prevent the unstable behavior, the spring constant over 10 N/m is required. We change the geometry of cantilever to satisfy this requirement. The thickness of the cantilever in effective part is increased from 6 μm to various thicknesses such as 10 μm , 15 μm , 20 μm , 30 μm , and the theoretical value of spring constants are 9.78 kHz, 33 kHz, 78.24 kHz and 264.06 kHz. We call these electrostatic actuators with different thickness of effective length as type C actuator. The displacement of type C actuators is evaluated by optical microscopy and probe station as well. In the case of type C actuators with 15 μm and 20 μm thickness of effective length, the applied voltage of both actuators are over than 300 V for actuation of cantilever. The cantilever is easily damaged by electrical breakdown when the applied is over than 300 V in air. Due to the cantilever is damaged by high voltage, the cantilever cannot be stuck on stoppers completely.

To demonstrate the capability of the SFM imaging, we install the fabricated probe in to a commercial SPM system. The length, width, and thickness of cantilever are 1900 μm , 50 μm , and 6 μm . The SFM imaging of Au grating pattern was obtained by fabricated electrostatic actuator in a contact mode and employing an external optical displacement sensor. On the other hand, we employ the fabricated electrostatic in the same SPM machine for evaluation of manipulation action with Latex beads. The sample is grounded, and manipulation is performed at SFM mode with actuation voltage of 180 V. The latex beads on a Si wafer are picked up by fabricated actuator using Van Der Waals force, and can be emitted to another place by electrostatic force by applying -50 V between the probe and the substrate.

This non-thermal type actuator using electrostatic pull-in effect is fabricated integrated with an extraction electrode without assembly process. This electrostatic is demonstrated that the spring constant of cantilever is tunable. The SFM imaging and manipulation action are obtained by fabricated electrode success. The application of this electrostatic actuator for TOF-MA SFM is possible in future.

論文審査結果の要旨

半導体微細加工技術を発展させたマイクロ・ナノ加工技術を用いると、さまざまな機能を集積化した小型のデバイスが実現できる。近年、新しい表面分析の方法として、走査型プローブ顕微鏡を用いて表面形状を観察し、狙った原子や分子を質量分析する飛行時間型質量分析－走査型力顕微鏡が提案されている。この顕微鏡では表面観察と質量分析という2つの測定モードを切り替えるために、アクチュエータを集積化したプローブが必要である。また、表面を安定して観察するために、プローブの共振周波数が高い必要がある。これまでに熱式や圧電式のアクチュエータを集積化したプローブの報告があるが、十分な変位量を確保するためには熱式ではプローブの駆動周波数が低く、圧電式では駆動特性にヒステリシスがあるため繰り返しの位置を再現できない問題があった。またこれまでのプローブでは引き出し電極を組み立てにより形成しているため、プローブ先端と電極の高精度の位置合わせが困難であった。静電駆動方式では形状によって周波数特性や変位量を高い自由度で設計でき、位置合わせ精度を達成できるが、一般に変位と高周波数特性の両立は難しく、用途ごとに異なる設計を必要とする。本論文は、上記問題を解決するため新しい静電駆動型の飛行時間型質量分析－走査型力顕微鏡用のアクチュエータ集積化プローブを提案し、その研究結果をまとめたもので、全編7章からなる。

第1章は序論であり、研究背景や目的について述べている。

第2章では、走査型プローブ顕微鏡の原理について述べ、その原理と特徴について論じている。これは飛行時間型質量分析－走査型力顕微鏡用のプローブの設計のための重要な知見である。

第3章では、静電アクチュエータの種類、構造やその特性についてまとめ、大きな変位を達成できる走査型力顕微鏡と相性の良いジッパー形静電アクチュエータの設計について論じている。この設計論を展開し、大きな変位を得るための構造の最適化手法について考察している。これは、静電アクチュエータを集積化したカンチレバーの駆動性能の向上のために重要な知見である。

第4章では、静電アクチュエータを集積化した飛行時間型質量分析－走査型力顕微鏡用のプローブを提案し、その設計とその基本性能について論じている。提案するシステムは、カンチレバーが大きく変位でき、観察モードごとの共振周波数がチューニングでき、精密に位置合わせされている引き出し電極などの機能が集積化されているもので、有効かつ重要な成果である。

第5章では、アクチュエータ集積化プローブの作製方法についてまとめている。作製に必要な加工技術の詳細およびジッパー型の静電アクチュエータのプローブへの集積化方法についてまとめている。これは有益な成果である。

第6章では、飛行時間型質量分析走査型力顕微鏡用プローブの駆動性能の評価結果についてまとめている。アクチュエータ集積化プローブは、静電駆動により最大 400 μm 変位し、変位に伴うプルイン現象によって表面観察時のカンチレバーの共振周波数が可変できることが実験的に示されている。また走査型プローブ顕微鏡としての動作、ナノパーティクルを利用した表面からのパーティクル操作ができることが示されている。これは飛行時間型質量分析－走査型力顕微鏡用プローブの応用として重要な成果である。

第7章は結論である。

以上要するに本論文は表面形状観察と質量分析の機能をあわせ持つ飛行時間型質量分析－走査型力顕微鏡用のプローブを開発して有効な成果を得たものであり、機械システムデザイン工学および精密工学の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。